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SPECTRAL MEASUREMENTS FROM 1.6 TO 5.4 MICRONS OF NATURAL SURFACES AND CLOUDS

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ABSTRACT

A spectrometer, utilizing an interference filter wedge, has been used to obtain spectra of reflected solar and emitted thermal radiation from earth in the wavelength interval 1.6 to 5.4 microns. Measurements were made, from a jet aircraft, of characteristic spectra of a wide variety of surface and cloud conditions during day and night flights. Measurements made concurrently from the airplane and the Nimbus II meteorological satellite verified the accuracy of the Nimbus measurements.

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INTRODUCTION

Laboratory reflectance measurements on a variety of earth surface minerals made by Hovis (1) indicated that emissivities in the 3.4 to 4.2 micron interval utilized by the Nimbus High Resolution Infrared Radiometer (HRIR) departed significantly from unity. The opportunity to measure the spectral distribution of radiated energy in this wavelength interval was available during a series of flights of NASA's Convair 990 jet aircraft. Existing interference filter wedges allowed the interval 1.6 to 5.4 microns to be scanned at a spectral resolving power of $\lambda/\Delta\lambda = 100$ with an instrument of great simplicity as described in the accompanying paper.(2)

Blau (3) has reported on scattering of sunlight by clouds but his spectra did not go beyond 3.6 microns and were all, of course, daytime measurements. Though the Nimbus HRIR was designed primarily for nighttime observations, it has been operated while viewing the sunlit earth. Therefore, spectral information from this experiment was desired to aid in the interpretation of the Nimbus HRIR daylight data.

The 1.6 to 5.4 micron interval also encompasses most of the strong spectral features of surface minerals that might be seen in reflected solar radiation, so flights were made over areas of known surface composition during daylight hours in an attempt to locate such features. The flights were at high altitudes and high aircraft speeds to simulate, as closely as possible, the atmospheric interference and motion smear of spatial resolution that would be experienced from an orbiting spacecraft attempting such measurements.

The 4.3 micron band of CO_2 was covered by the filter wedge but no attempt was made to accurately cover the complete band since some method of signal compression would have been necessary to obtain useful sensitivity with target temperatures ranging from 215°K in the center of the CO_2 band immediately outside the airplane to the 300°K range of the surface seen in the atmospheric windows. Signal compression would have diluted the principle aim of the experiment for little gain so it was not used. Though the entire 4.3 micron band is shown in all the spectra for continuity, data for effective radiance temperatures less than 240°K is doubtful in accuracy.

The airplane flights also provided a good field test of the filter wedge spectrometer in the harsh environment of the unpressurized, unheated tail cone of a

high altitude aircraft. Several extremely rough landings on earthquake-ravaged runways in South America provided vibration and shock tests that proved the rugged character of the instrument. (It should be emphasized that the rough landings were entirely the fault of the runways and were in no way caused by the pilots of the plane who did an outstanding job under trying conditions.)

In the course of two months of operation hundreds of spectra were obtained so the results presented herein are obviously selected examples. A complete atlas of spectra is in preparation but will exceed the capacity of any journal.

NIGHTTIME MEASUREMENTS WITH NIMBUS II

Simultaneous measurements from an aircraft and an orbiting satellite require a target that can be identified from both vehicles and that is either highly uniform or has some distinctive characteristic that both could identify. The results of Nimbus I as reported by Nordberg (4) showed that the Salar de Atacama in Northern Chile was such a target. The salar appears on nighttime HRIR pictures as a crescent shaped area with a warm outer ring defining the outline and a cooler center. The Atacama Desert is extremely dry and the salar is high, approximately 2300 meters, so atmospheric attenuation between the aircraft and satellite measurements is minimized. An aircraft beacon in the coastal town of Antofagasta allows accurate navigation to locate the salar at night.

Shortly before and after local midnight of May 23-24, 1966 the salar was overflown several times concurrent with the Nimbus II overpass. The spectra showed no significant departure from gray body behavior but did show a temperature profile corresponding to the shape of the salar. Figure 1 illustrates one profile with four maxima corresponding to the warm edges of the salar. The edges are keyed to the representation showing the rough shape of the salar and the airplane path. The HRIR picture of the salar is from Nimbus I which, due to its lower orbital altitude, has finer spatial resolution than Nimbus II, and the pictures, after printing, show features more readily. Comparison of the profile obtained with the Nimbus II analog trace showed agreement to within 2°C with the spectrometer temperature usually the higher of the two.

DAYLIGHT TERRAIN MEASUREMENTS

Flights during clear sky conditions were made over many types of surface conditions, sometimes with great variety in a short space of time due to the speed of the plane. One interesting example is shown in Figure 2 with three spectra taken over Nevada. The plane overflew Carson Sink, forested mountains
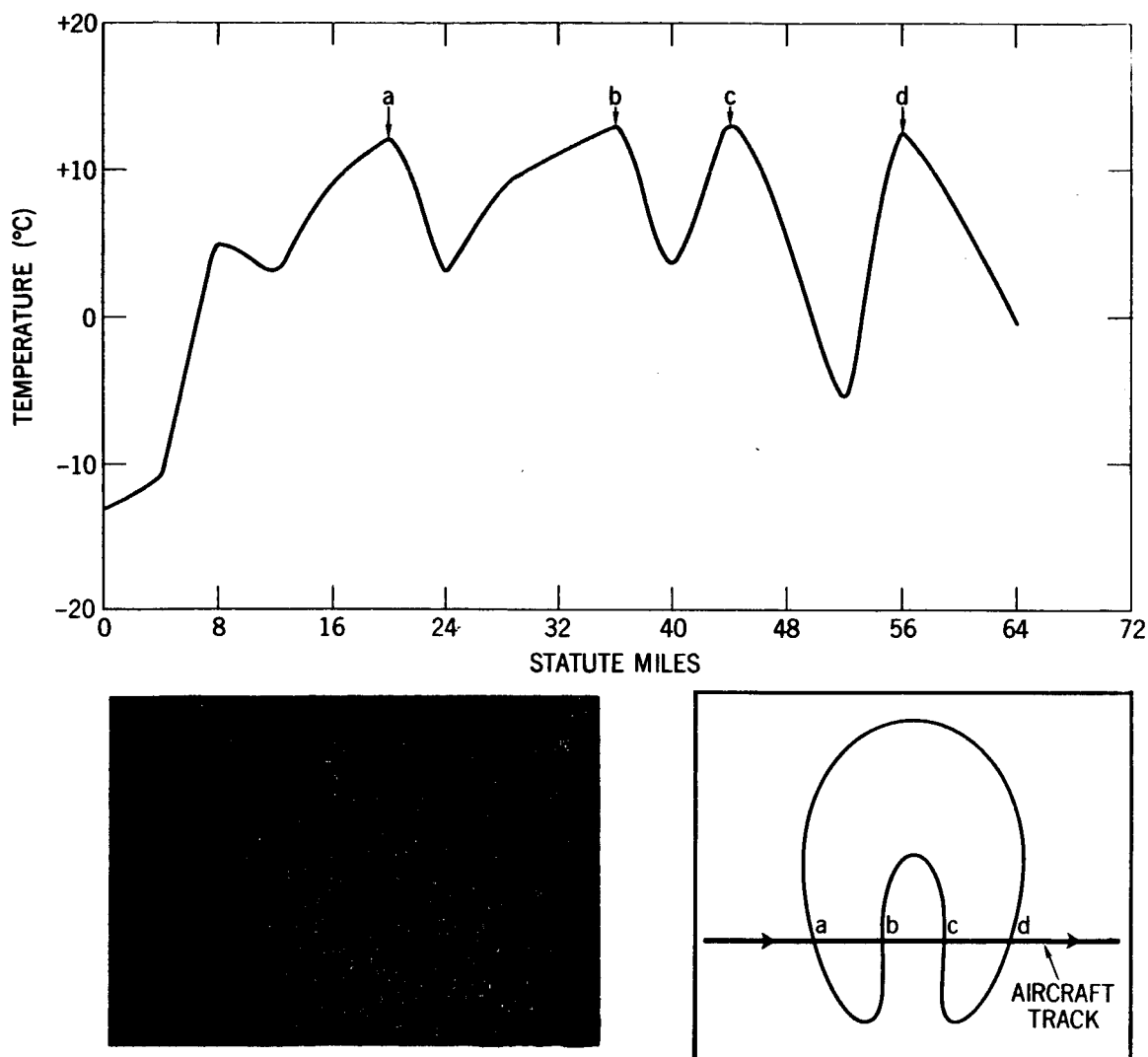
Figure 1. Radiative Temperature over Salar de Atacama, Chile

near Lake Tahoe and the lake in the space of 12 minutes from 2318 to 2330 U.T. on April 26, 1966 at an altitude of 11.3 km. The spectra are presented with the zero line as the reference blackbody at 273°K with signal levels above and below. Short of 3 microns the thermal emission of the reference blackbody can be considered to be zero when compared to the reflected solar energy. Beyond 3 microns the signal appears above and below the zero line as the target is warmer or colder than the reference blackbody. The energy scale is different by a factor of ten either side of 3 microns to keep the reflected energy on scale and still show some detail in the 3 to 5.4 micron interval. This format will be followed in all spectra presented as it seems to be the easiest with which to identify spectral characteristics.
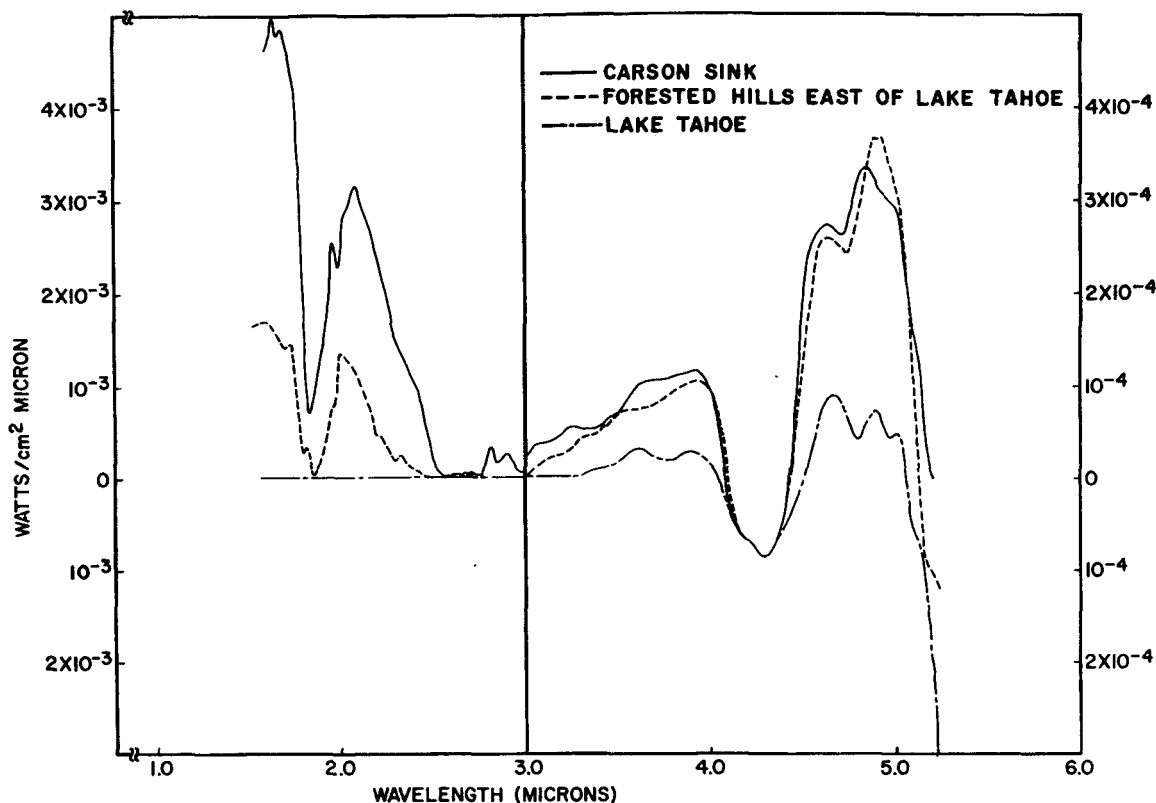
Figure 2. Spectra from 11.3 km over Nevada

The three spectra in Figure 2 illustrate some extremes in reflectance in the shorter wavelength interval varying from the flat desert terrain of Carson Sink with a relatively high reflectance through the darker forests with snow to the lake with no measurable diffuse reflectance. Since all spectra were taken looking straight down, no specular reflectance or sun glint is seen. Longward of 3 microns the contrast is mainly due to temperature differences though some reflected sunlight is mixed with thermal emission from 3 to 4 microns. Complicating the situation near 3 microns is the wing of the 2.7 micron water vapor band absorbing sunlight through two passes and thermal radiation from the surface through one pass. This complexity strongly indicates that little useful information about either the surface or the atmosphere of earth can be obtained from the 3.0 to 3.4 micron interval.

The 3.4 to 4.0 micron interval is a reasonably good atmospheric window and contains several characteristic reflectance features of minerals, particularly carbonates. A close comparison of the data from Carson Sink with laboratory reflectance measurements shows that none of the character of the spectra is identifiable as due to a particular surface mineral.

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From 4.0 microns longward the radiation appears due solely to thermal emission modified by the atmospheric bands of CO_2, H_2O and N_2O.

On the same flight the Sacramento Valley of California was overflown at an altitude of 11.3 km with an outside air temperature of -57°C. The spectra shown in Figure 3 were taken between 2343 and 2345 U.T. over the highly cultivated valley. Except for the quantitative inference that the reflectance in the 1.6 to 3.0 micron interval is lower than the desert area of Carson Sink while not as low as the water of Lake Tahoe no particular spectral character would identify the area below as heavily vegetated. The quantitative argument is rather weak in that there are non-vegetated surface covers with lower reflectance than desert terrain that could simulate the Sacramento Valley condition. The absence of any spectral feature that could be uniquely attributed to organic material over such a densely cultivated area indicates that this spectral region is not attractive for remote sensing of life.

Figure 4 compares the airplane data taken over White Sands National Monument with a laboratory measurement of reflectance of a sample of the gypsum
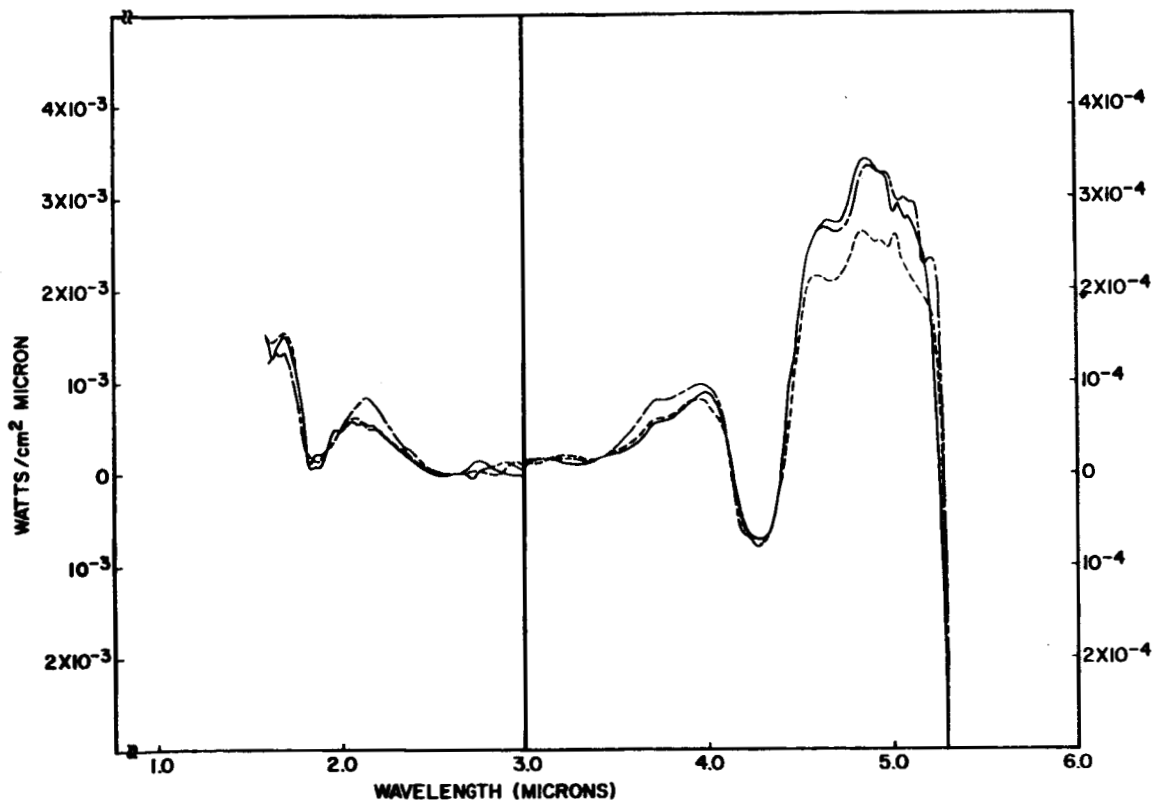

Figure 3. Sequential Spectra from 11.3 km over Sacramento Valley, California
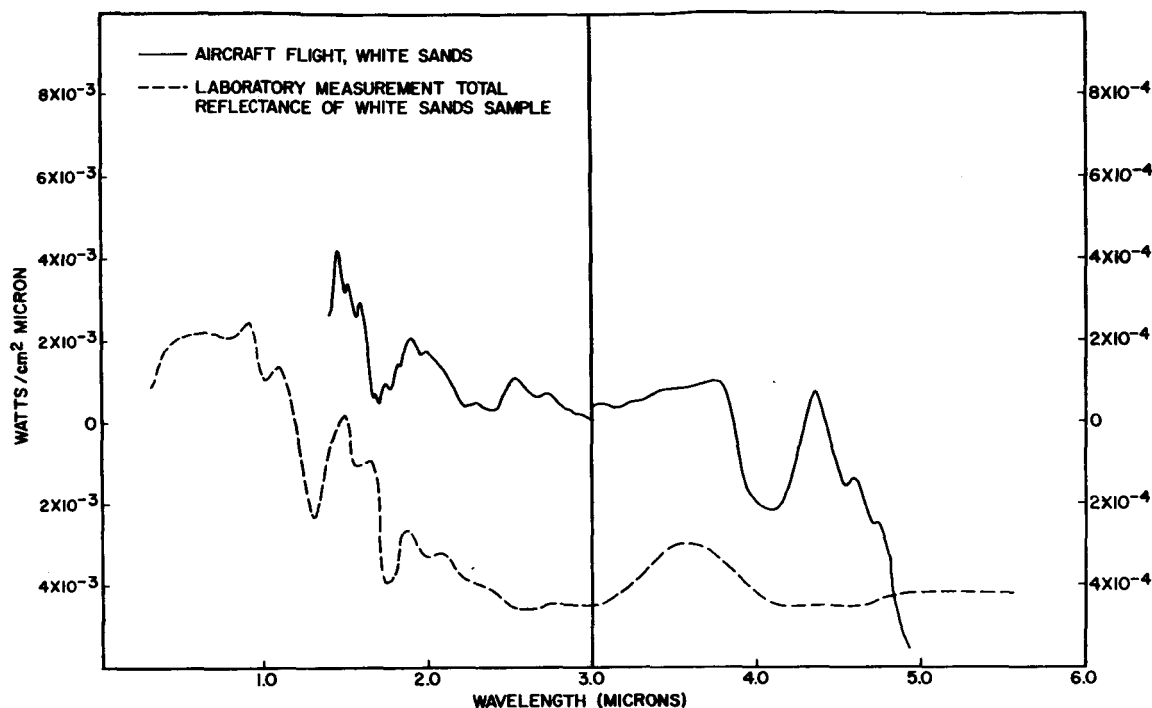
Figure 4. Spectrum from 7.6 km over White Sands, New Mexico

sand from White Sands. Unfortunately some haze was noticeable in the area the day the spectra were taken which may have obscured surface features to some degree.

CLOUD MEASUREMENTS

Most cloud measurements were made in daylight hours to determine the extent of mixture of emitted thermal and reflected solar radiation in the 3.4 to 4.2 micron interval. Figure 5 shows three spectra taken over a solid stratocumulus layer within the interval from 1742 to 1744 U.T. just east of Atlanta, Georgia on May 11, 1966. Plane altitude was 10.0 km and outside air temperature was -43°C. Reflected solar energy clearly predominates to 3.6 microns where a downturn occurs as thermal emission becomes dominant. The partial window at 4.6 microns indicates an equivalent blackbody temperature of about 273°K, but the high humidity over Georgia in May has probably partially closed the "window."

A low stratus layer was encountered on May 30, 1966 at the coast of Peru just south of Lima. The spectra shown in Figure 6 were taken between 1637 and 1639 U.T. from an altitude of 12.2 km over the stratus. These clouds are very
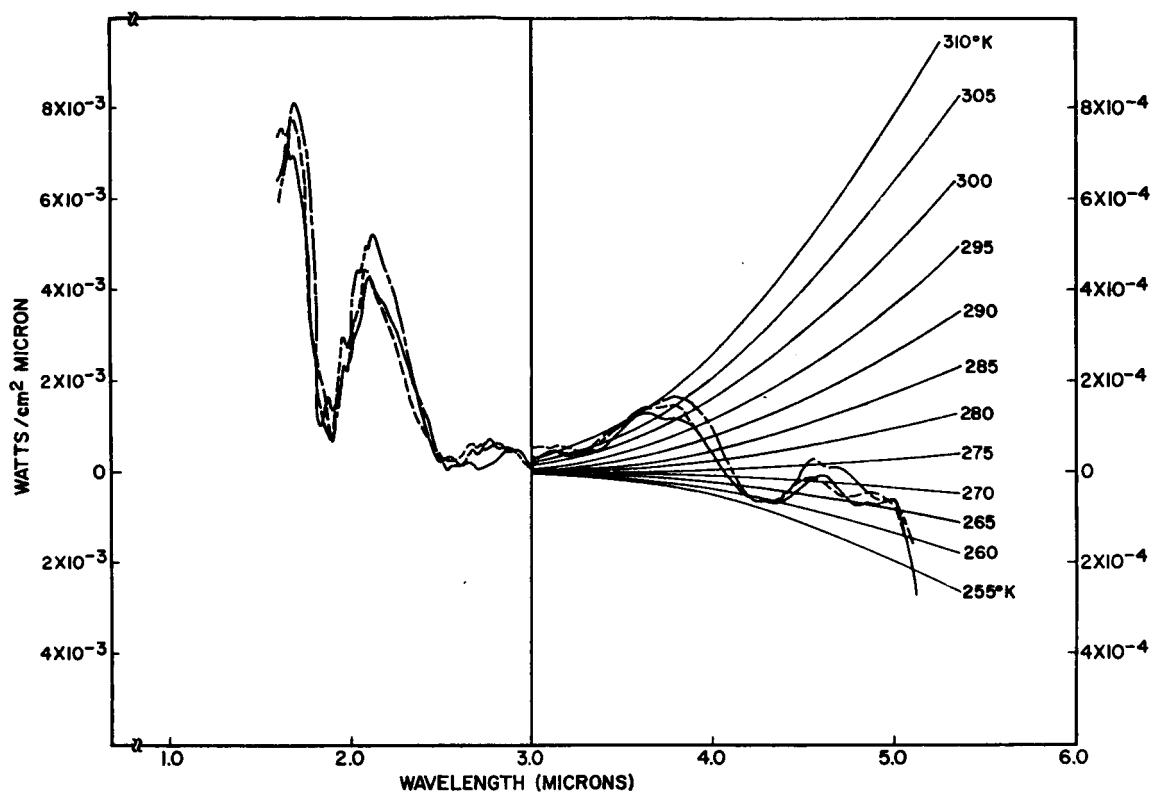
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Figure 5. Sequential Spectra from 10.0 km over Strato Cumulus Clouds

bright in the 1.6 to 1.7 micron region and the 2.1 to 2.2 micron interval. These low clouds, considerably warmer than those seen near Atlanta shown in Figure 4, do not show the pronounced maximum at 3.6 microns seen in the colder clouds since emitted thermal energy is compensating for diminishing solar energy out to 4.0 microns where CO_2 absorption begins to diminish the radiant energy reaching the spectrometer. The reflectance of the clouds from 3.6 to 4.0 microns is considerably less than that in the peaks at 1.6 to 1.7 and 2.1 to 2.2 microns where it is in the 60 to 65% region. At 3.7 microns for instance, using Johnson's (5) solar irradiance data, the reflectance would be only approximately 11% even if thermal emission is ignored. If we assume the cloud at a reasonable temperature such as 290°K for such stratus, the thermal contribution reduces the reflectance to approximately 4.5%.

A fairly dense layer of cirrus clouds was encountered on May 30, 1966 over the ocean near Lima, Peru. The spectra shown in Figure 7 were taken between 1906 and 1908 U.T. on that day. The clouds were just below the plane flying at an altitude of 12.2 km with an outside air temperature of -55°C. At this low a temperature reflected solar radiation predominates in the entire 3.4 to 4.2 micron interval even though the reflectance is of the order of 1%. Reflectance is
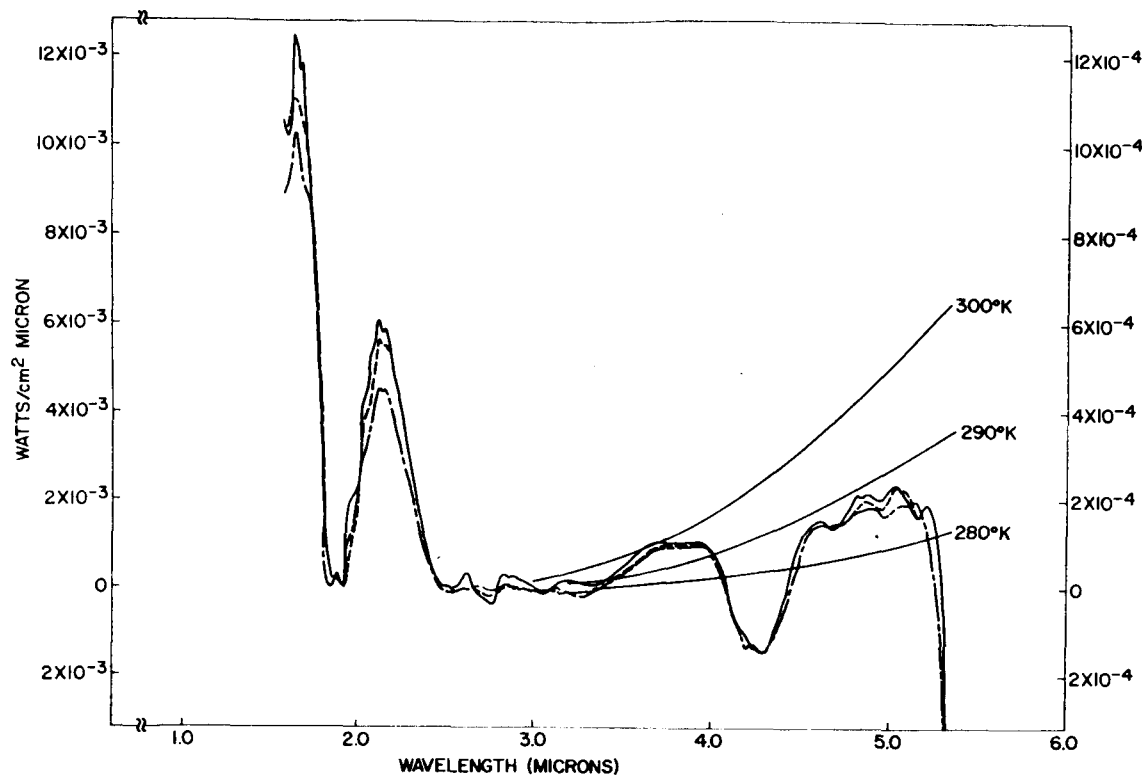
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Figure 6. Sequential Spectra from 12.2 km over Low Stratus Clouds

similarly lower than that of the stratus of the previous example in the 1.7 and 2.2 micron peaks.

CONCLUSIONS

Within the 3.4 to 4.2 micron interval covered by the Nimbus HRIR variations in surface emissivity caused no appreciable error in temperature measurements. The rapid rate of change at night of radiant energy with temperature in this spectral interval largely compensates for emissivity changes for the range of earth temperatures encountered. Future infrared scanning radiometers operating from 10 to 12 microns, to completely avoid reflected solar radiation will be more sensitive to emissivity variations, but can operate day and night measuring only emitted thermal radiation.

The cloud reflectances measured, though low, vary sufficiently so that it would be difficult if not impossible to separate reflected and emitted radiation in daylight and hence determine cloud temperatures and by inference altitude using a 3.4 to 4.2 micron wavelength interval.
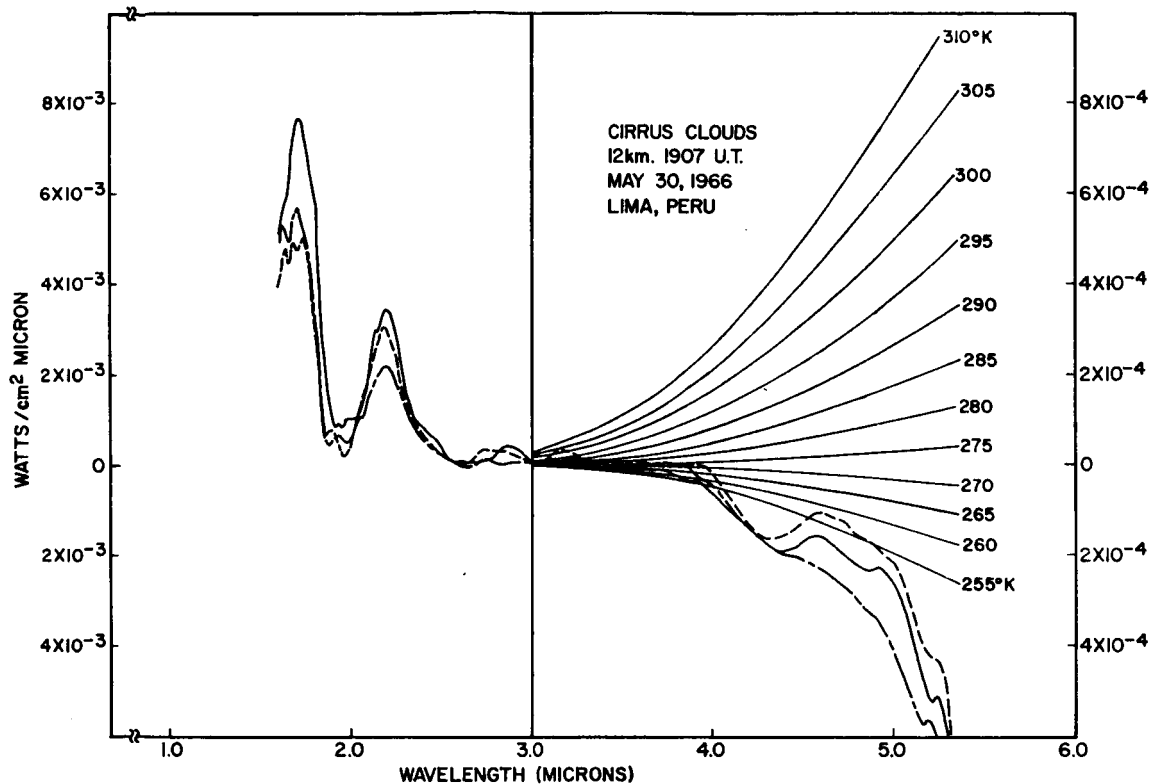
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Figure 7. Sequential Spectra from 12.0 km over Cirrus Clouds

Daylight terrain measurements show a disappointing lack of information concerning the constituents of the surface layer. Perhaps empirical comparison could be used to determine surface character if the general nature of the surface is known, i.e., desert, forest, cultivated farmland, etc., but the combination of atmospheric attenuation and ground smear has effectively eliminated any easily identifiable and unique characteristics that would allow positive identification of the nature of the surface layer. Image motion compensation could be used to ease the ground smear problem, but the atmospheric problem, acute from an airplane, would be even worse from an earth orbiting satellite.

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